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Blockage Testing in the NASA Glenn 225 Square Centimeter Supersonic Wind Tunnel*

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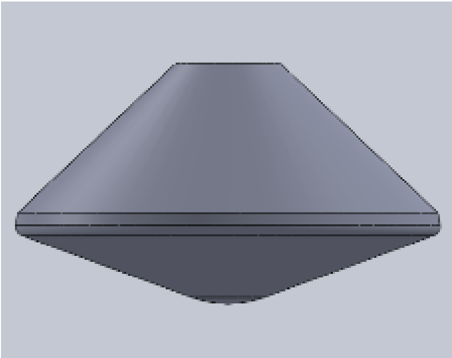
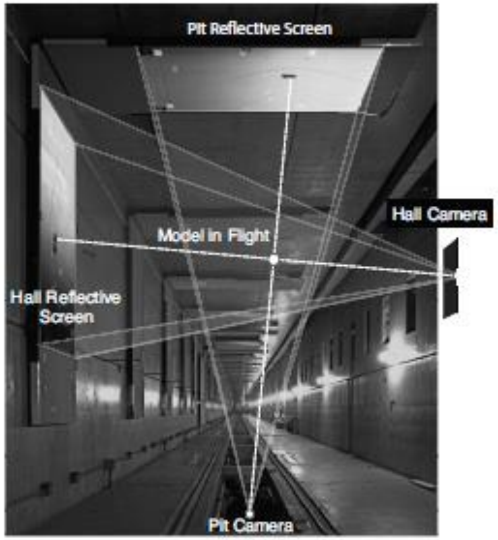
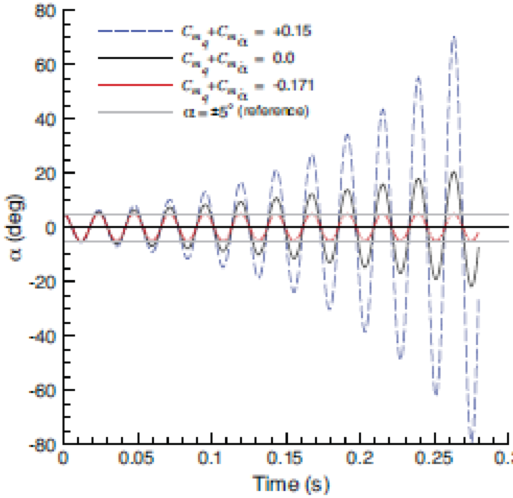
Background

- Project to Support Magnetic Suspension System for Testing Dynamic Stability of Blunt Body Entry Vehicles
- Past Test Methods for vehicle include Ballistic Range Testing
  - Use shadowgraph technique to capture model’s position and angle down test range
  - Accurate flight dynamics from free-flying test, but simulation fit to trajectory provides no good options for data reduction
- Exploring use of Magnetic Suspension System in Supersonic Wind Tunnel
  - Still provides free-flying test set-up, but more controlled environment
  - Electronic Positioning System provides 3 DOF control, allowing model to oscillate around center of gravity

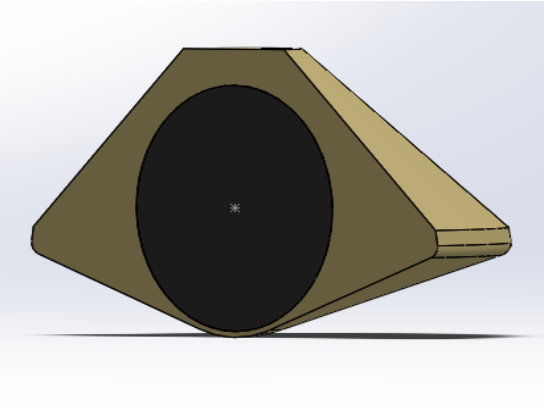






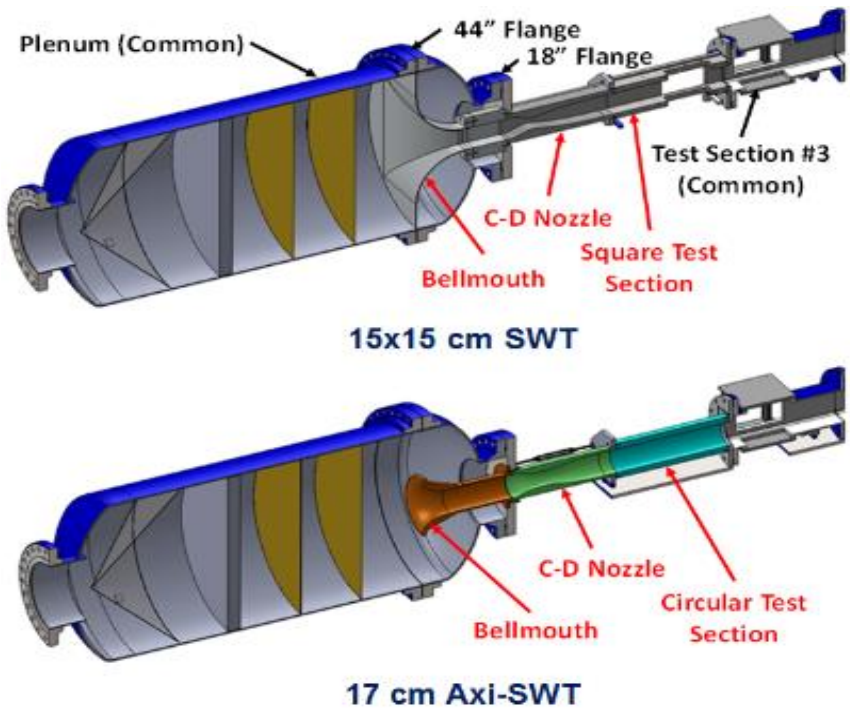
Magnetic Suspension System

- Magnetic Suspension System will react against aerodynamic and gravitational forces to suspend model
- MIT proposed Magnetic Suspension System at NASA Langley HFA Tunnel at Mach 10, 1966
  - Typical test models: Cones with semi vertex angles ranging from 10-40 degrees
  - 6 DOF magnetic control and EPS position feedback
- NASA LaRC/GRC will use tunnel for measuring dynamic stability of blunt bodies
  - Model will be comprised of spherical iron core surrounded by non-magnetic materials
  - EPS System well suited for position feedback, difficult to optically track blunt body
  - Flight dynamics will be recorded with high speed cameras
- Subsonic tunnel pathfinder for supersonic magnetic balance design



Facility

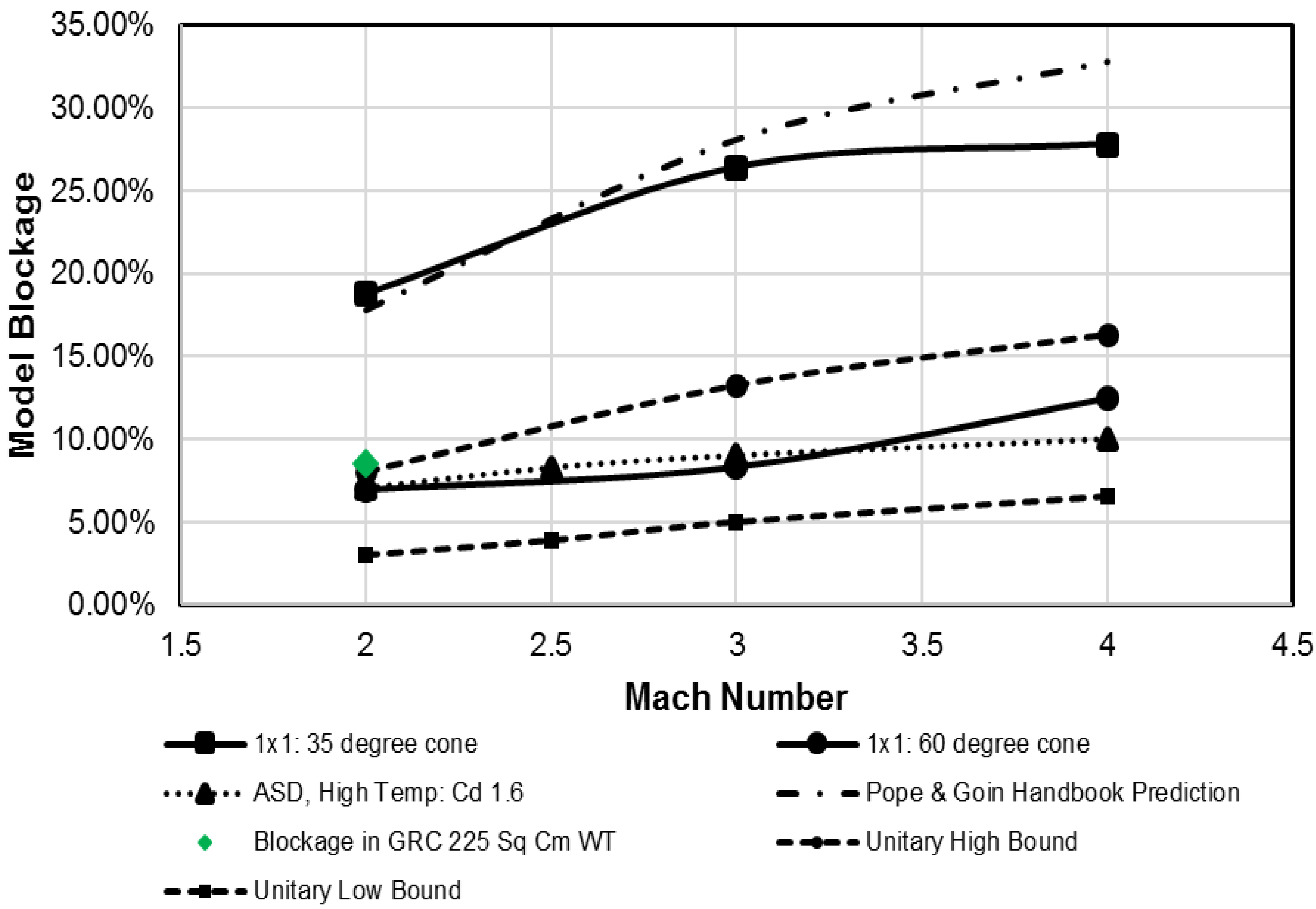
- NASA GRC 225 cm^2 Supersonic Wind Tunnel
  - Total Pressure: .276 MPa
  - Vacuum Pressure: 88 kPa
  - Continuous Flow Facility
- Contains nozzle and blocks for:
  - Mach 2, 2.5, and 3 w/ Square Test Section (15 cm side)
  - Mach 2.5 Axisymmetric Test Section (17 cm diameter)
- Square Test Sections contain windows allowing for Schlieren capability



Research Objectives

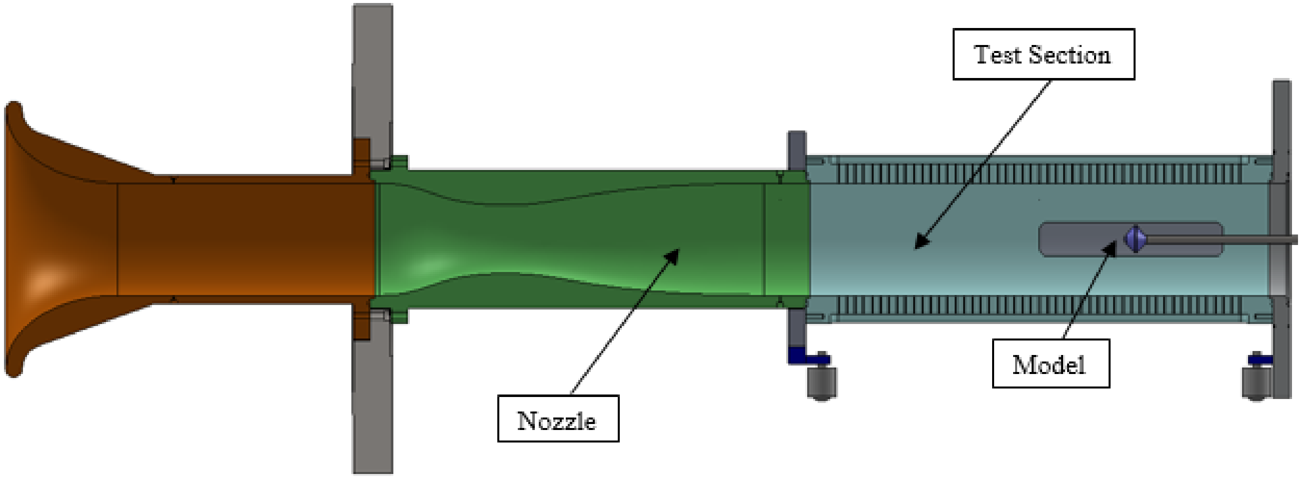
- Minimizing Magnetic Field Strength
  - Sizing Test Models with Blockage Tests
    - $F_{Drag} = qSC_D$
    - $F_{Magnetic} = V(m \times \nabla)H$
    - Tunnel Start
  - Determine largest model possible (Fmagnetic~r^3 and Fdrag~r^2)
  - Determining Lowest Possible Dynamic Pressure (decreases Drag)

Literature Review

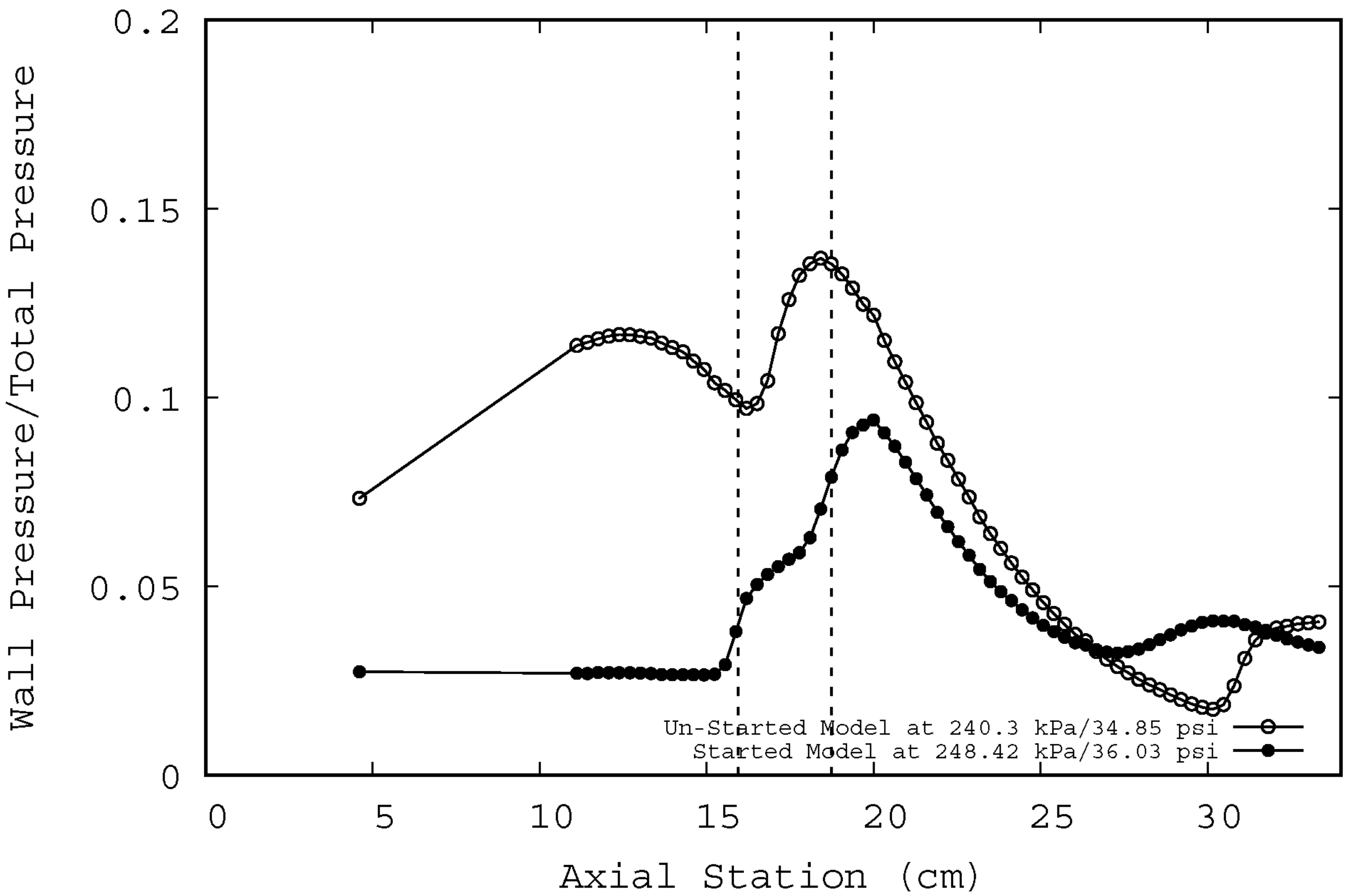


Blockage Tests

- 3D printed test matrix of varying model sizes and cone angles
- Cone angles selected to be 45, 60 and 70 degree models
- Models were tested at Mach 2, 2.5 and 3 with Square Test Section and at Mach 2.5 with Axisymmetric Test Section
- Total Pressure increased incrementally until model started
  - Maximum Reynolds Number corresponded to 310 kPa or 45 psia or a mass flow of 5.4 kg/s or 12 lb/s
- After start occurred, total pressure decreased incrementally until model unstarted

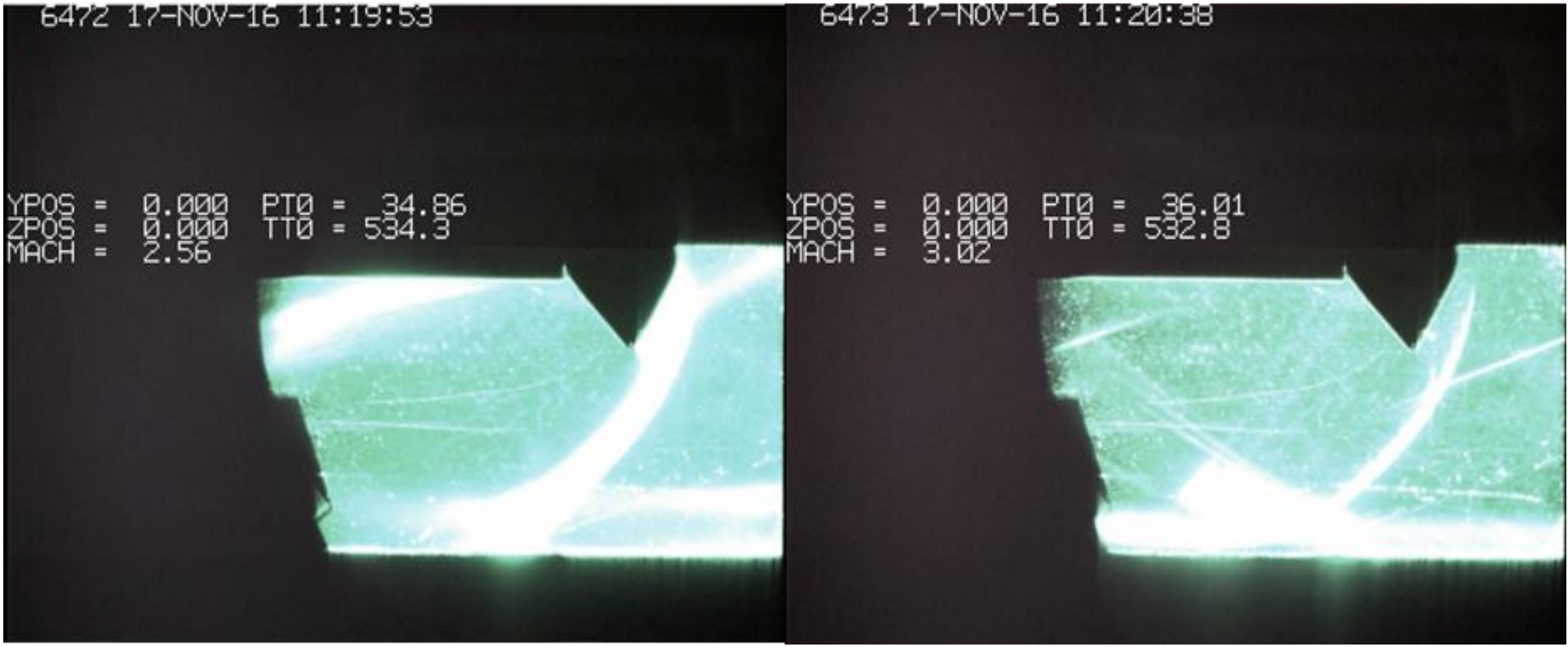


Blockage Tests: Wall Pressure Tap Data



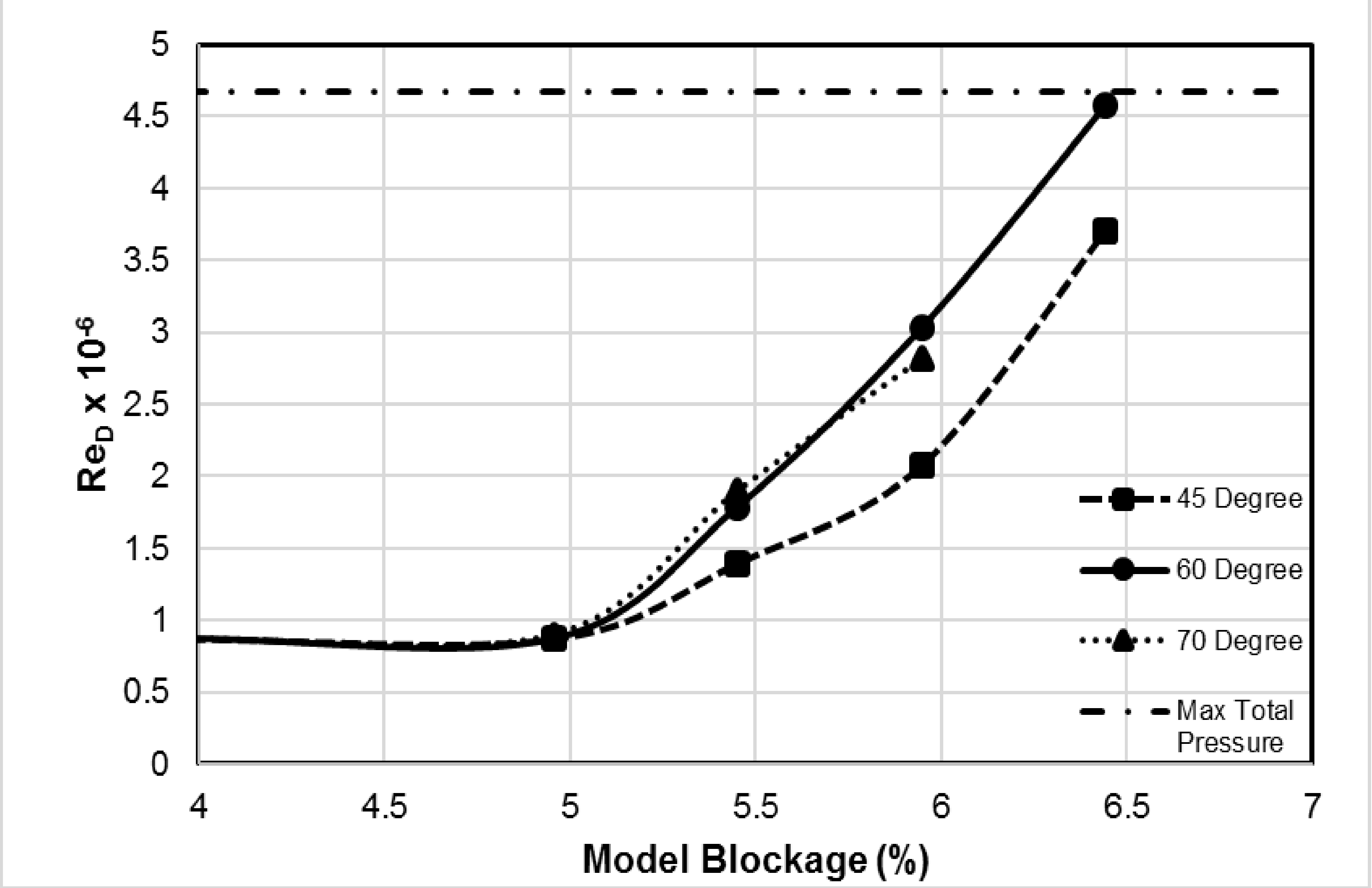
Model 6007.5 at Mach 3

Blockage Tests: Schlieren Data

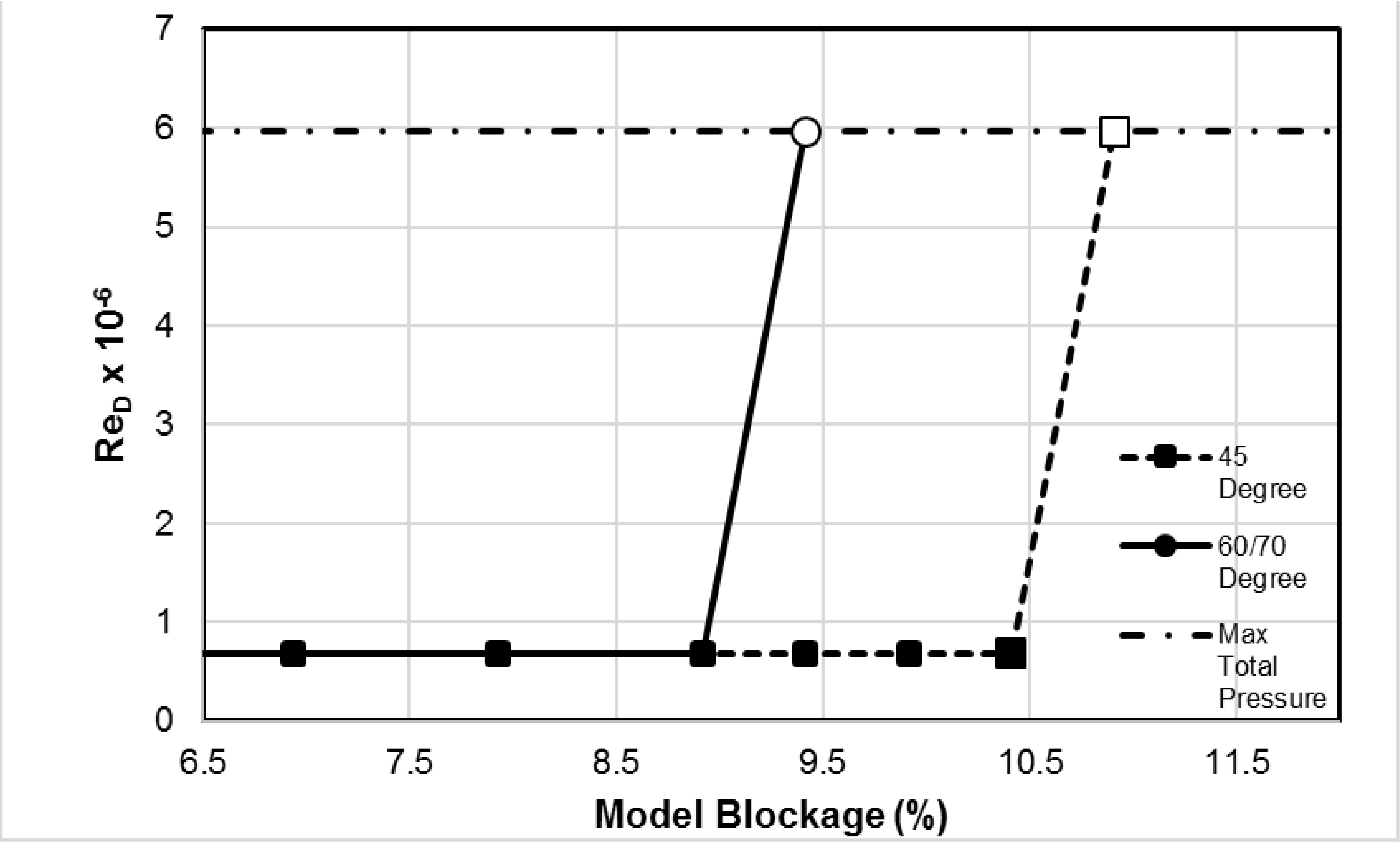


Model 6007.5 at Mach 3
(L) Unstarted, (R) Started

Blockage Test: Mach 2.5 Axisymmetric Nozzle 50.8 cm



Blockage Test: Mach 2.5 Axisymmetric Nozzle: 10.2 cm

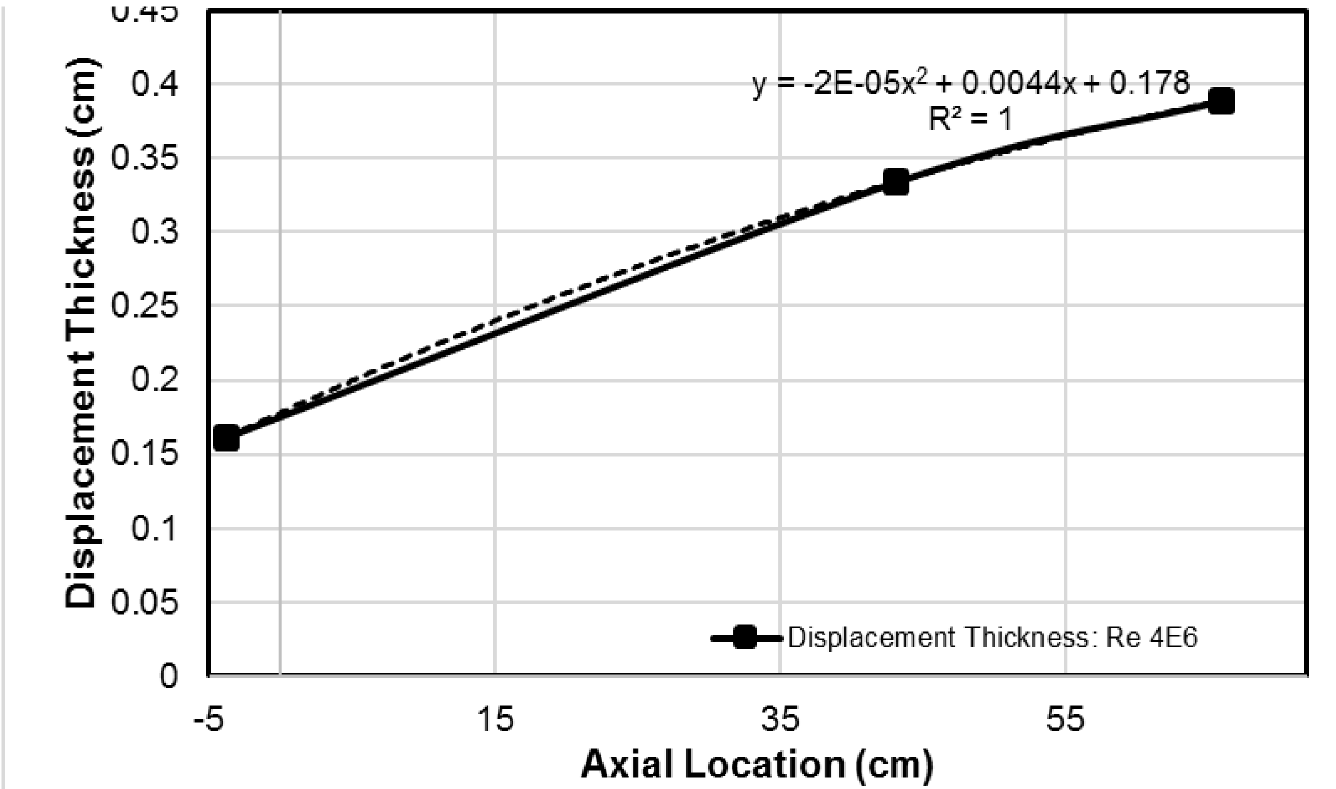


- Model Same Size for 60 and 70 degree model

Boundary Layer Correlation Depending on Axial Location

- Data taken in former study in Mach 2.5 Axisymmetric Test Section

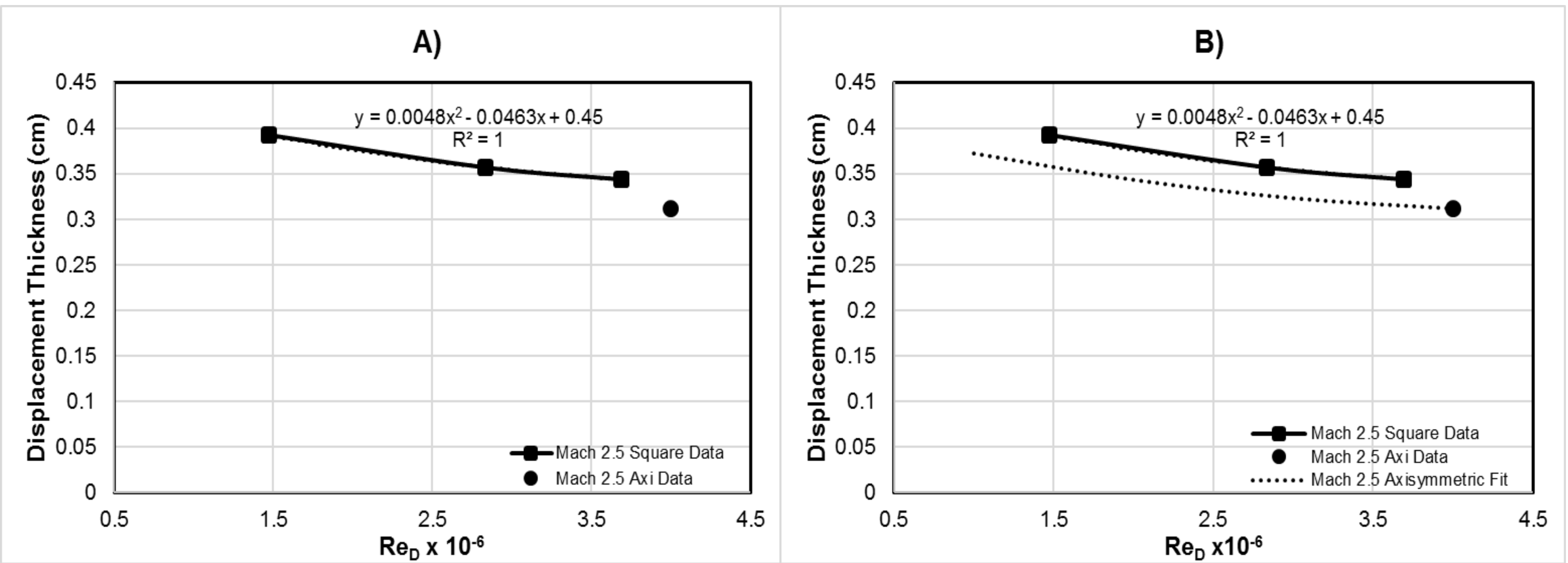
Model Distance (cm)	Disp Thickness (cm)	BL Blockage (cm^2)
8.573	0.214	11.298
49.213	0.346	18.108



Boundary Layer Correlation Depending on Axial Location

- Previous data taken at different Reynolds number than blockage testing Re_D of $4x10^6$
- Data taken in another study in Mach 2.5 Square Test Section that compares Re_D vs displacement thickness

$Rex10^6$	δ^* (cm)
0.984	0.392
1.89	0.357
2.46	0.344



Boundary Layer Correlation Depending on Axial Location

		x10^6	cm	cm	%
Back	**Model**	**Re**	**δ* at 36.56 cm**	**δ* at 50.8 cm**	**Blockage**
70	6.0%	2.822	0.3232	0.359	8.269%
60	6.5%	4.573	0.3011	0.3345	7.715%
45	6.5%	3.706	0.3089	0.3432	7.913%

Front	**Model**	**Re**	**δ* at 36.56 cm**	**δ* at 10.2 cm**	**Blockage**
70	9.0%	0.68	0.38355	0.2192	5.090%
60	9.0%	0.68	0.38355	0.2192	5.090%
45	10.5%	0.68	0.38355	0.2192	5.090%

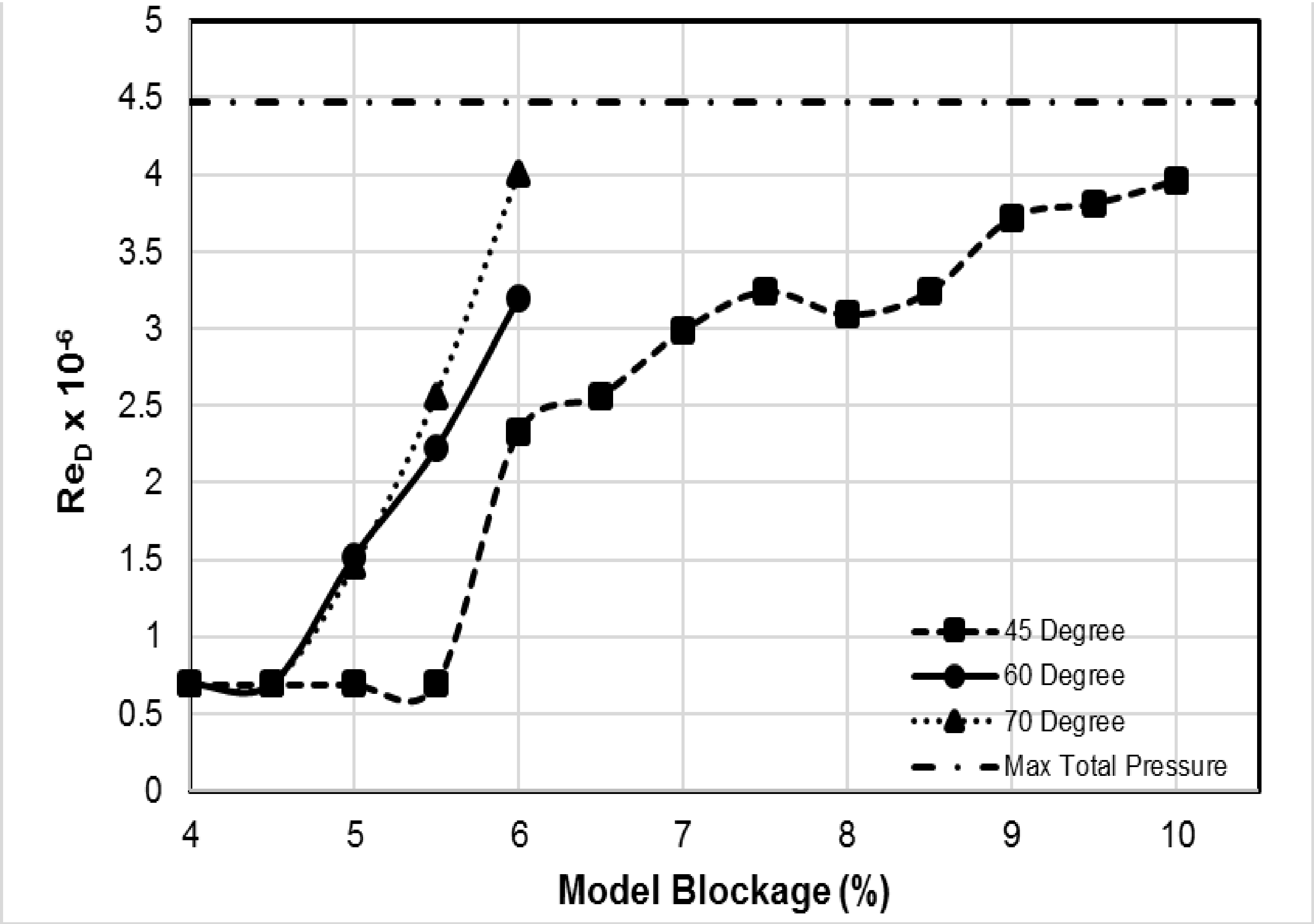
$$\frac{A_{BL}}{A_{test}} = \frac{2R\delta^* - {\delta^*}^2}{R^2}$$

Boundary Layer Correlation Depending on Axial Location

Location	Cone	Model	BL Blockage	Total Blockage
10.2 cm	70	9.0%	5.09%	14.01%
50.8 cm	70	6.0%	8.27%	14.22%
10.2 cm	60	9.0%	5.09%	14.01%
50.8 cm	60	6.5%	7.72%	14.16%
10.2 cm	45	10.5%	5.09%	15.50%
50.8 cm	45	6.5%	7.91%	14.36%

- Much larger models can be tested at front of test section due to reduced boundary layer blockage
- Test section can be designed to be shorter in length because of likely testing location near front

Blockage Test: Mach 2.5 Square Test Section: 18.7 cm from Nozzle



Comparison of Boundary Layer Blockage between Mach 2.5 Square and Axisymmetric Test Sections

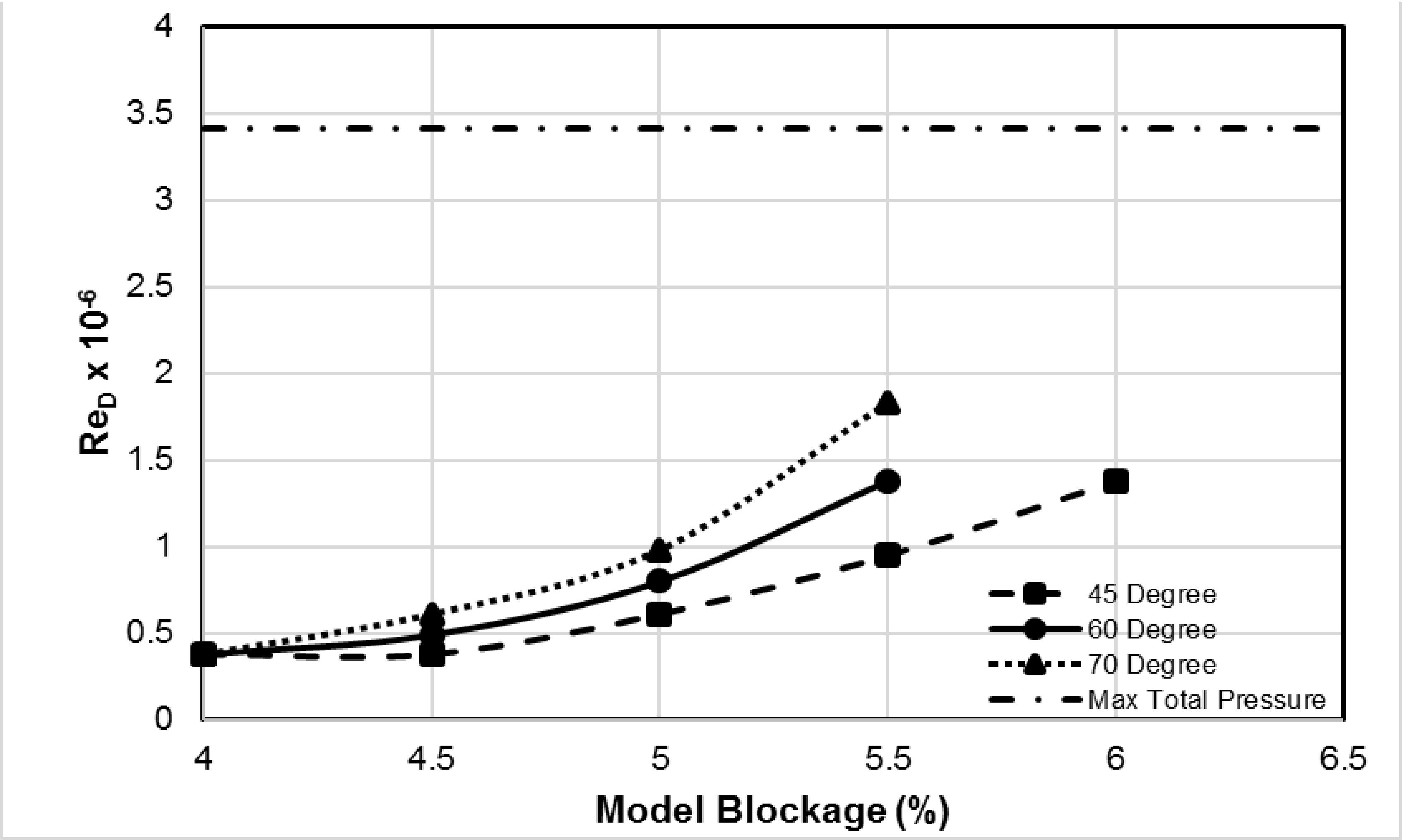
- C_{CG} is "corner growth coefficient" approximates boundary layer blockage at corners
  - Adjusted to be 1.087 or 8.7% to match total blockage of 60 degree model

$$\frac{A_{BL\ Blockage}}{A_{test\ section}} = C_{CG}\,\frac{L_{test}^2 - (\,L_{test} - 2\,\delta^*)^2}{L_{test}^2}$$

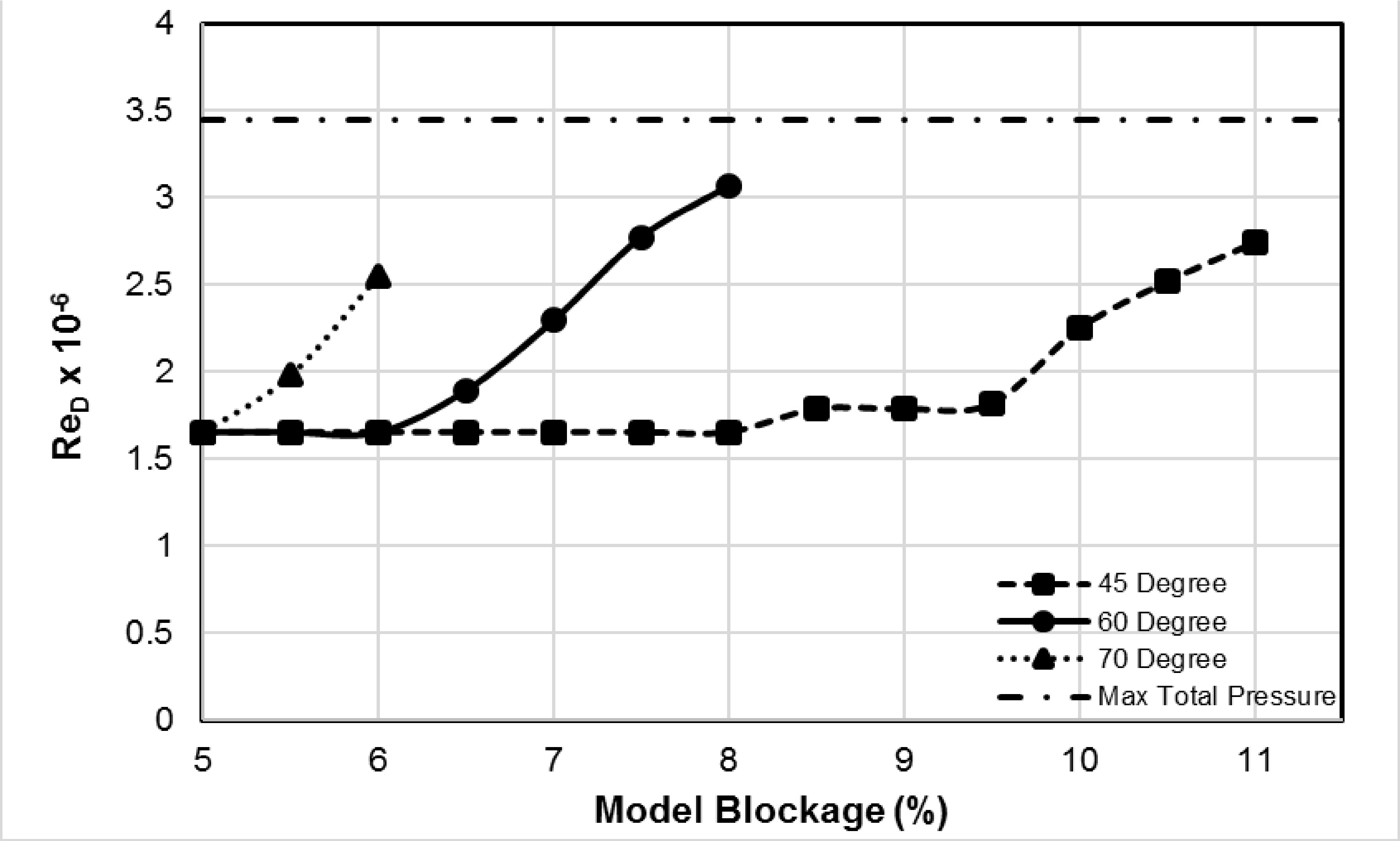
Location	Cone	Model	BL Blockage	Total Blockage
Axi-10.2 cm	70	9.0%	5.09%	14.01%
Axi-50.8 cm	70	6.0%	8.27%	14.22%
Square	70	6.0%	7.87%	13.87%
Axi-10.2 cm	60	9.0%	5.09%	14.01%
Axi-50.8 cm	60	6.5%	7.72%	14.16%
Square	60	6.0%	8.09%	14.09%
Axi-10.2 cm	45	10.5%	5.09%	15.50%
Axi-50.8 cm	45	6.5%	7.91%	14.36%
Square	45	10.0%	7.88%	17.88%

- Square test section has comparable boundary layer blockage as 50.8 cm in Axisymmetric Test Section

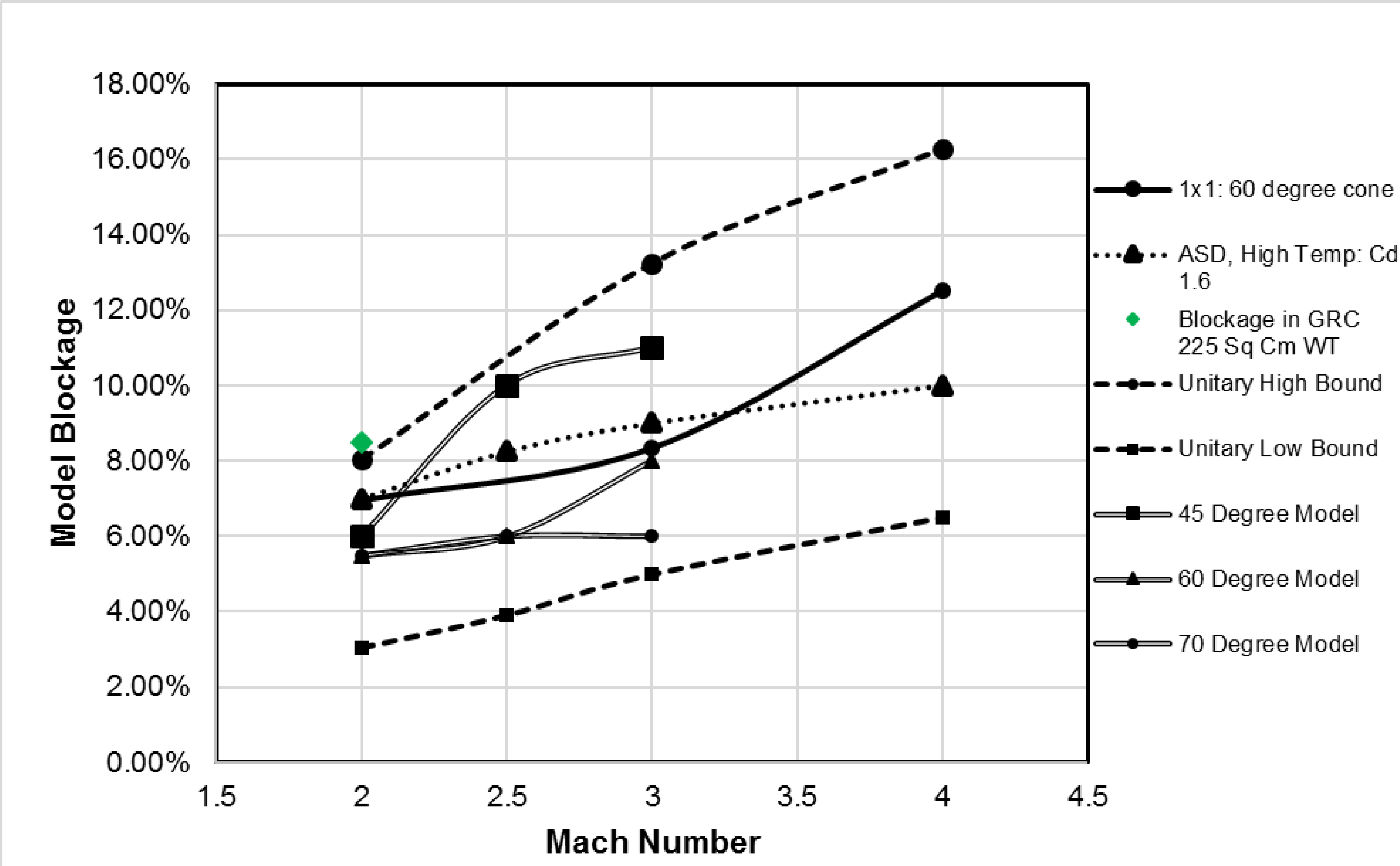
Blockage Test: Mach 2 Square Test Section: 18.7 cm from Nozzle



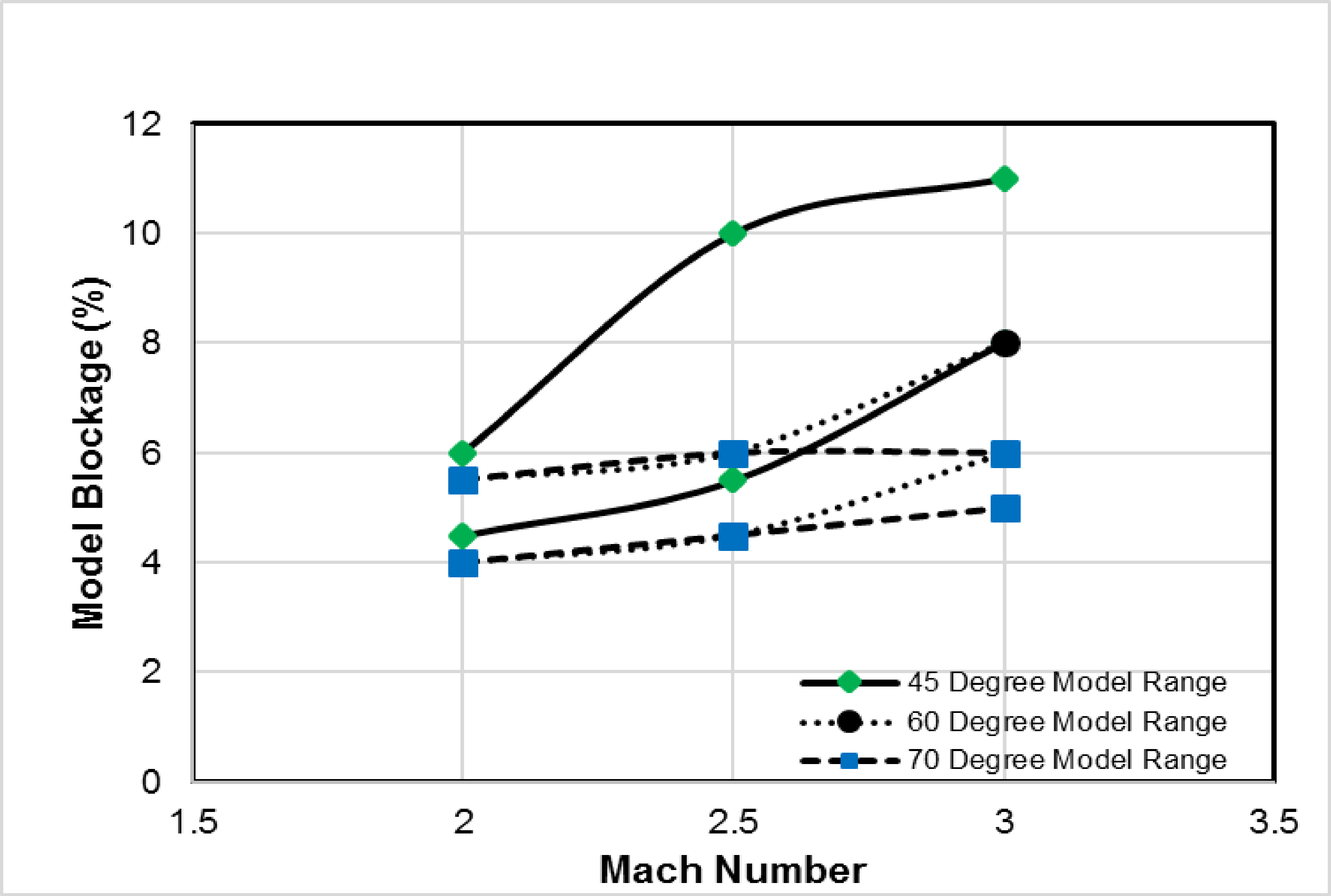
Blockage Test: Mach 3 Square Test Section: 18.7 cm from Nozzle



Literature Study Revisited



Blockage vs Mach Number



Lowest Re_D Before Unstart For Blockage Testing

Configuration	$Re_D \times 10^6$
Mach 2 Square	.56-.66
Mach 2.5 Axi at 50.8 cm	.68-.75
Mach 2.5 Square	.6-1.14
Mach 3 Square	.68-.81

- Mach 2.5 Axisymmetric at 10.2 cm Re_D couldn't be decreased further since it started at the lowest possible Re_D
- Mach 2.5 Square tested over two days 2 weeks apart which had differing total temperatures from ~10 R
- Re_D can be reduced greatly after tunnel start occurs which indicates starting Re_D will likely not be operating Re_D

Starting Loads Analysis

Test Section	Mach	Cone Angle	Size	q (kPa)	Cd	Fdrag (N)
Square	2	70	5.5%	19.71	1.58	38.53
Square	2	60	5.5%	15.91	1.46	28.75
Square	2	45	6.0%	19.71	1.3	34.59
Square	2.5	70	6.0%	20.18	1.58	43.05
Square	2.5	60	6.0%	16.42	1.46	32.36
Square	2.5	45	10.0%	20.53	1.3	60.05
Axi-50.8cm	2.5	70	6.0%	19.60	1.58	41.80
Axi-50.8cm	2.5	60	6.5%	21.72	1.46	46.37
Axi-50.8cm	2.5	45	6.5%	17.64	1.3	33.53
Axi-10.2cm	2.5	70	9.0%	3.23	1.58	10.34
Axi-10.2cm	2.5	60	9.0%	3.23	1.46	9.55
Axi-10.2cm	2.5	45	10.5%	3.23	1.3	9.92
Square	3	70	6.0%	10.14	1.58	21.63
Square	3	60	8.0%	12.52	1.46	32.91
Square	3	45	11.0%	10.95	1.3	35.24

- Loading calculations approximates bow shock in front of model as normal shock

Steady State Load Analysis

Test Section	Mach	Cone Angle	Size	q (kPa)	Cd	Fdrag (N)
Square	2	70	5.5%	6.477	1.58	12.66
Square	2	60	5.5%	6.477	1.46	11.70
Square	2	45	6.0%	6.477	1.3	11.37
Square	2.5	70	5.5%	4.767	1.58	10.17
Square	2.5	60	5.5%	4.767	1.46	9.40
Square	2.5	45	6.5%	4.767	1.3	13.94
Axi-50.8cm	2.5	70	6.0%	4.767	1.58	10.17
Axi-50.8cm	2.5	60	6.5%	4.767	1.46	10.18
Axi-50.8cm	2.5	45	6.5%	4.767	1.3	9.06
Axi-10.2cm	2.5	70	9.0%	4.767	1.58	15.25
Axi-10.2cm	2.5	60	9.0%	4.767	1.46	14.09
Axi-10.2cm	2.5	45	10.5%	4.767	1.3	14.64
Square	3	70	6.0%	3.679	1.58	7.85
Square	3	60	8.0%	3.679	1.46	9.67
Square	3	45	11.0%	3.679	1.3	11.84

- Steady State Total Pressure Determined to be 48.2 kPa (7 psi) for Mach 2, 62.05 kPa (9 psi) for Mach 2.5, and 82.74 kPa (12 psi) for Mach 3

Conclusions

1) Provided blockage chart that can be used for approximate sizing of test models and magnetic suspension system during design
2) Determined it is advantageous to test near nozzle to reduce boundary layer blockage and increase allowable model blockage
3) Determined axisymmetric test section has less significant boundary layer blockage compared with square test section
4) Proved it was possible to significantly decrease total pressure after start occurred which will lower performance requirements for the magnetic suspension system

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